

CERN-TH/2002-033  
February 2002

# Strong Primordial Inhomogeneities and Galaxy Formation

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## Abstract

The new element of theory of galaxy formation, strong primordial inhomogeneities, is shown to be a reflection of unstable large scale structures of topological defects, created in second order phase transitions in the inflationary Universe. In addition to *archholes-like* large scale correlation of the primordial inhomogeneity of energy density of coherent scalar field oscillations, the same mechanism, based on the second order phase transitions on the inflationary stage and the domain wall formation upon the end of inflation, leads to the formation of massive black hole clusters that can serve as nuclei for the future galaxies. The number of black holes with  $M \sim 100M_{\odot}$  and above is comparable with the number of galaxies within the modern cosmological horizon. The primordial fractal structure of galaxies can find natural grounds in the framework of model we developed. The proposed approach offers the physical basis for new scenarios of galaxy formation in the Big Bang Universe.

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February 2002

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# 1 INTRODUCTION

The origin of galaxies and of the observed structure of their inhomogeneous distribution in FRW cosmology is generally ascribed to the development of gravitational instability on the matter - dominant stage, leading to the slow growth of small initial density fluctuations on the nearly homogeneous expanding background. According to modern cosmology the spectrum of initial density fluctuations is generated on the inflationary stage. Particle theory offers a physical basis for both inflation and dark matter, dominating in the development of gravitational instability. However, the impact of particle physics in the problem of galaxy formation seems to be much stronger, adding new non-trivial elements to the theory of cosmological structure formation. One such new element, which is a rather general cosmological consequence of the particle symmetry breaking pattern, is the structure of strong primordial large scale inhomogeneities, tracing the large scale structure of cosmological defects, generated in second order phase transitions in the inflationary Universe.

The existence of topological defects reflects the non-trivial topological properties of broken particle symmetry. So, a magnetic monopole solution follows from compact Lie group breaking, leaving unbroken the  $U(1)$  symmetry of electromagnetism, which is the general case for GUT models. In some of these, the conditions for cosmic string and domain wall solutions are realized. The cosmological effect of these topologically stable solutions is widely recognized as an effective tool to probe the scenarios of very early Universe and the particle models underlying them. Recall that magnetic monopole overproduction [1] has put severe constraints on GUT models and stimulated the creation of inflationary cosmology [2], whereas the domain wall problem [3] constrained the models of spontaneous CP violation [4]. On the other hand, topological defects represent a new element of galaxy formation, as it takes place in cosmic string cosmology [5].

However, the actual amount of primordial magnetic monopoles produced in the inflationary Universe is still a big question, whereas the conditions for stable wall and string solutions are not very general for particle models (see the review [6]). A much wider class of these models possesses the symmetry breaking pattern, which can be effectively described by pseudo-Nambu–Goldstone (PNG) field and which corresponds to the formation of an unstable topological defect structure in the early Universe.

The Nambu–Goldstone nature in such an effective description reflects the spontaneous breaking of global symmetry, resulting in continuous degeneracy of vacua. The explicit symmetry breaking at smaller energy scale changes this continuous degeneracy by discrete vacuum degeneracy. At high temperatures such a symmetry breaking pattern implies the succession of second order phase transitions. In the first transition, continuous degeneracy of vacua leads, at scales exceeding the correlation length, to the formation of topological defects in the form of a string network; in the second phase transition, continuous transitions in space between degenerated vacua form the surfaces: domain walls surrounded by strings. This last structure is unstable, but, as was shown in the example of the invisible axion [7], it is reflected in the large scale inhomogeneity of distribution of energy density of coherent PNG (axion) field oscillations. The role of inflation in the creation of this inhomogeneity is indirect, since it provides identical initial conditions of expansion in causally

disconnected regions, which provides the simultaneous high temperature phase transition and the formation of structure of topological defects (axionic strings) that spreads far beyond the cosmological horizon in that period.

Second order phase transitions on the inflationary stage result in more non-trivial influence of superluminal expansion on the forms of topological defects and properties of their structure. The result depends on the relationship between the symmetry breaking scales and Hubble constant on inflationary stage; it leads to various observational consequences, related to various strong primordial inhomogeneities. Among these consequences, systematic study of which we approach, there appears a new interesting way of formation of primordial galactic nuclei, to be discussed in the present paper.

Now there is no doubt that the centres of almost all galaxies contain massive black holes [8]. An original explanation of the formation of such supermassive black holes assumes the collapse of a large number of stars in the galaxy centres. However, the mechanism of the galactic nuclei formation is still unclear. According to [9], there are serious grounds to believe that the formation of stars and galaxies proceeded simultaneously. On the other hand, in the work [10] a model of galaxy formation around a massive black hole was considered and arguments in its favour were presented. Each of the two approaches has certain advantages, while being neither free of drawbacks.

We will consider below a new mechanism describing the very early formation of primordial black holes (PBHs), which serve as the nucleation centres in the subsequent formation of galaxies. This mechanism may prove to be free from disadvantages inherent in the models based on the concept of a single PBH being the nucleus of the future galaxy.

Previously [11] we proposed a mechanism of the PBHs formation that opens the possibility of massive black hole formation in the early Universe. The mechanism is based on the fact that black holes can be created as a result of a collapse of closed vacuum walls formed during a second order phase transition. The masses of such black holes may vary within broad limits, up to the level  $\sim 10^8 M_\odot$ .

To figure out the idea [11], let us assume that a potential of some scalar field possesses at least two different vacuum states. In such a situation there are two quantitatively different possibilities to distribute these states in the early Universe. The first possibility implies that the Universe contains approximately equal amounts of both vacuum states, which is typically the case at the usual thermal phase transition. The alternative possibility corresponds to the case when the two vacuum states are populated with different probabilities. In this case, islands of a less probable vacuum state surrounded by a sea of another, more probable vacuum state appear. As was shown in [11], an important condition for such an asymmetric distribution is the existence of effectively flat valleys in the scalar field potential during inflation. Under this condition the scalar field can be considered as a massless scalar field additional to inflaton, existing on the inflationary de Sitter background. It is well known that the inflationary fluctuations can essentially change the value of a massless scalar field, while the inflation itself blows up wavelengths of these fluctuations. These two factors define the space distribution of a scalar field, which is still massless until a certain moment. Thus, even though the phase transition itself takes place only after the end of inflation, deeply in the Friedman–Robertson–Walker (FRW) epoch, the initial distribution

of the scalar field is already defined at the inflation period, in such a way that there are eventually, islands representing one vacuum in the sea of another vacuum.

It is supposed that after the phase transition, the two vacuum states are separated by a vacuum wall. The initial distribution of the scalar field formed during the inflation stage allows the formation of closed walls of sizes significantly exceeding the cosmological horizon at the moment when the phase transition just takes place. At some instant after crossing the horizon, such walls become causally connected as a whole and begin to contract because of the surface tension. As a result, provided that friction is small and the wall does not radiate a considerable part of its energy in the form of scalar waves, almost all the energy of a closed wall may be focused within a small volume inside the gravitational radius. This is the necessary condition for a black hole formation. The mass spectrum of black holes formed by this mechanism depends on parameters of the scalar field potential determining the direction and size of the potential valley during inflation and the post-inflation phase transition. Although we deal here with the so-called PNG field, the proposed mechanism is quite general. The presence of massive PBHs is a new factor in the development of gravitational instability in the surrounding matter and may serve as a basis for new scenarios of the formation and evolution of galaxies.

## 2 PRIMORDIAL BLACK HOLE FORMATION

Now we will describe a mechanism accounting for the appearance of massive walls of a size essentially greater than the horizon at the end of inflation. Let us consider a complex scalar field with the potential

$$V(\varphi) = \lambda(|\varphi|^2 - f^2/2)^2 + \delta V(\theta), \quad (1)$$

where  $\varphi = r e^{i\theta}$ . This field coexists with an inflaton field which drives the Hubble constant  $H$  during the inflationary stage. The term

$$\delta V(\theta) = \Lambda^4 (1 - \cos \theta), \quad (2)$$

reflecting the contribution of effects to the Lagrangian renormalization (see for example [12]), is negligible on the inflationary stage and during some period in the FRW expansion. In other words, the parameter  $\Lambda$  vanishes with respect to  $H$ . The omitted term (2) begins to play a significant role only at the moment, after inflation, when the Hubble parameter sharply decreases with time ( $H = 1/2t$  during the radiation dominated epoch). Also, we assume the mass of the radial field component  $r$  always to be sufficiently large with respect to  $H$ , which means that the complex field is in the ground state even before the end of inflation. Since the term (2) is negligible during inflation, the field has the form  $\varphi \approx f/\sqrt{2} \cdot e^{i\theta}$ , the quantity  $f\theta$  acquiring the meaning of a massless field.

At the same time, the well established behaviour of quantum field fluctuations on the de Sitter background [13] implies that the wavelength of a vacuum fluctuation of every scalar field grows exponentially, having a fixed amplitude. Namely, when the wavelength

of a particular fluctuation, in the inflating Universe, becomes greater than  $H^{-1}$ , the average amplitude of this fluctuation freezes out at some non-zero value because of the large friction term in the equation of motion of the scalar field, whereas its wavelength grows exponentially. Such a frozen fluctuation is equivalent to the appearance of a classical field that does not vanish after averaging over macroscopic space intervals. Because the vacuum must contain fluctuations of every wavelength, inflation leads to the creation of more and more new regions containing a classical field of different amplitudes with scale greater than  $H^{-1}$ . In the case of an effectively massless Nambu–Goldstone field considered here, the averaged amplitude of phase fluctuations generated during each e-fold (time interval  $H^{-1}$ ) is given by

$$\delta\theta = H/2\pi f. \quad (3)$$

Let us assume that the part of the Universe observed inside the contemporary horizon  $H_0^{-1} = 3000h^{-1}\text{Mpc}$  was inflating, over  $N_U \simeq 60$  e-folds, out of a single causally connected domain of size  $H^{-1}$ , which contains some average value of phase  $\theta_0$  over it. When inflation begins in this region, after one e-fold, the volume of the Universe increases by a factor  $e^3$ . The typical wavelength of the fluctuation  $\delta\theta$  generated during every e-fold is equal to  $H^{-1}$ . Thus, the whole domain  $H^{-1}$ , containing  $\theta_0$ , after the first e-fold effectively becomes divided into  $e^3$  separate, causally disconnected domains of size  $H^{-1}$ . Each domain contains almost homogeneous phase value  $\theta_0 \pm \delta\theta$ . Thereby, more and more domains appear with time, in which the phase differs significantly from the initial value  $\theta_0$ . A principally important point is the appearance of domains with phase  $\theta > \pi$ . Appearing only after a certain period of time during which the Universe exhibited exponential expansion, these domains turn out to be surrounded by a space with phase  $\theta < \pi$ . The coexistence of domains with phases  $\theta < \pi$  and  $\theta > \pi$  leads, in the following, to the formation of a large-scale structure of topological defects.

The potential (1) possesses a  $U(1)$  symmetry, which is spontaneously broken, at least, after some period of inflation. Note that the phase fluctuations during the first e-folds may, generally speaking, transform eventually into fluctuations of the cosmic microwave radiation, which will lead to imposing restrictions on the scaling parameter  $f$ . This difficulty can be avoided by taking into account the interaction of the field  $\varphi$  with the inflaton field (i.e. by making parameter  $f$  a variable [14]). This spontaneous breakdown is holding by the condition of smallness of the radial mass,  $m_r = \sqrt{\lambda_\phi} > H$ . At the same time the condition

$$m_\theta = \frac{2f^2}{\Lambda} \ll H \quad (4)$$

on the angular mass provides the freezing out of the phase distribution until some moment of the FRW epoch. After the violation of condition (4) the term (2) contributes significantly to the potential (1) and explicitly breaks the continuous symmetry along the angular direction. Thus, potential (1) eventually has a number of discrete degenerate minima in the angular direction at the points  $\theta_{min} = 0, \pm 2\pi, \pm 4\pi, \dots$ .

As soon as the angular mass  $m_\theta$  is of the order of the Hubble rate, the phase starts oscillating about the potential minimum, initial values being different in various space

domains. Moreover, in the domains with the initial phase  $\pi < \theta < 2\pi$ , the oscillations proceed around the potential minimum at  $\theta_{min} = 2\pi$ , whereas the phase in the surrounding space tends to a minimum at the point  $\theta_{min} = 0$ . Upon ceasing of the decaying phase oscillations, the system contains domains characterized by the phase  $\theta_{min} = 2\pi$  surrounded by space with  $\theta_{min} = 0$ . Apparently, on moving in any direction from inside to outside of the domain, we will unavoidably pass through a point where  $\theta = \pi$  because the phase varies continuously. This implies that a closed surface characterized by the phase  $\theta_{wall} = \pi$  must exist. The size of this surface depends on the moment of domain formation in the inflation period, while the shape of the surface may be arbitrary. The principal point for the subsequent considerations is that the surface is closed. After reheating of the Universe, the evolution of domains with the phase  $\theta > \pi$  proceeds on the background of the Friedman expansion and is described by the relativistic equation of state. When the temperature falls down to  $T_* \sim \Lambda$ , an equilibrium state between the "vacuum" phase  $\theta_{vac} = 2\pi$  inside the domain and the  $\theta_{vac} = 0$  phase outside it is established. Since the equation of motion corresponding to potential (2) admits a kink-like solution (see [15] and references therein), which interpolates between two adjacent vacua  $\theta_{vac} = 0$  and  $\theta_{vac} = 2\pi$ , a closed wall corresponding to the transition region at  $\theta = \pi$  is formed. The surface energy density of a wall of width  $\sim 1/m \sim f/\Lambda^2$  is of the order of  $\sim f\Lambda^2$ <sup>1</sup>.

Note that if the coherent phase oscillations do not decay for a long time, their energy density can play the role of CDM. This is the case, for example, in the cosmology of the invisible axion (see [17] and references therein).

It is clear that immediately after the end of inflation, the size of domains which contains a phase  $\theta_{vac} > 2\pi$  essentially exceeds the horizon size. This situation is replicated in the size distribution of vacuum walls, which appear at the temperature  $T_* \sim \Lambda$  whence the angular mass  $m_\theta$  starts to build up. Those walls, which are larger than the cosmological horizon, still follow the general FRW expansion until the moment when they get causally connected as a whole; this happens as soon as the size of a wall becomes equal to the horizon size  $R_h$ . Evidently, internal stresses developed in the wall after crossing the horizon initiate processes tending to minimize the wall surface. This implies that the wall tends, first, to acquire a spherical shape and, second, to contract toward the centre. For simplicity, we will consider below the motion of closed spherical walls<sup>2</sup>.

The wall energy is proportional to its area at the instant of crossing the horizon. At the moment of maximum contraction, this energy is almost completely converted into kinetic energy. Should the wall at the same moment be localized within the gravitational radius, a PBH is formed.

Detailed consideration of BH formation was performed in [21]. We proceed below to study the formation of a PBH cluster in the early Universe.

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<sup>1</sup>The existence of such domain walls in theory of the invisible axion was first pointed out in [16].

<sup>2</sup>The motion of closed vacuum walls has been driven analytically in [18, 19].

### 3 CORRELATIONS IN THE BLACK HOLE DISTRIBUTION

Previously [11, 21] we had studied a new process involving the formation of uncorrelated PBHs in the Universe. It was demonstrated that a model with reasonable parameters readily provides for the formation of  $\sim 10^{11}$  massive (with the mass  $10^{30}$ - $10^{40}$ g. each) black holes, which coincides with the number of galaxies in the observed part of the Universe. In that analysis, we did not take into account correlations (inherent in this mechanism) between the formation of a massive black hole and the appearance of smaller black holes surrounding it. This correlation is related primarily to certain features of the above-discussed process of the formation of domains with phases  $\theta > \pi$ . It seems that the appearance of such domains creates prerequisites for the formation of new, smaller domains inside. Let us estimate the mass distribution of these daughter domains. Consider a region with a size of the order of  $H^{-1}$  and a phase within  $\pi < \theta_0 < \pi + \delta$  (where  $\delta = H/2\pi f$  is the average phase jump during the  $H^{-1}$  time period), formed during the inflation period as a result of fluctuation in a certain region of space of phase  $\theta < \pi$ . During the next e-fold, this space domain will be divided in  $e^3$  subdomains with size  $H^{-1}$ , and some of these will acquire a phase  $\theta_1$  in the interval  $\pi - \delta < \theta_1 < \pi$ . Upon the subsequent phase transition, these domains will be separated by walls from the external region. Similar transitions, when crossing the phase  $\theta = \pi$  in the reverse direction, will take place in each subdomain during the next e-fold. Thus, a structure of the fractal type appears <sup>3</sup> which reproduces itself in each time step on a decreasing scale.

Let  $\zeta$  denotes the number of subdomains formed in each step, around which a wall may appear with time. Apparently, this value obeys the inequality  $1 < \zeta \ll e^3$ . In the subsequent estimates, we will assume that  $\zeta \approx 2$ – $3$ . Since each causally connected domain touches approximately six neighboring domains, we can hardly expect  $\zeta$  to be greater for a total number of  $\sim e^3 \approx 20$ . The mass of the future black hole (if this would actually form) is determined by the area of a closed surface with the phase  $\theta = \pi$ . The ratio of areas of the initial (mother) and daughter domains is readily estimated: the initial area, after a single e-fold, is  $S_0 \approx e^2 H^{-2}$ , and the daughter subdomain area is  $S_1 \approx H^{-2}$ . Therefore, the ratio of masses of the black holes belonging to two sequential generations is

$$M_j/M_{j+1} \approx S_j/S_{j+1} \approx e^2, \quad (5)$$

for a relative number of them assumed to be

$$N_{j+1}/N_j = \zeta. \quad (6)$$

As is readily seen, the number and mass of black holes appearing upon the  $j$ -th e-fold after the initial domain formation are determined by parameters of the largest black hole

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<sup>3</sup>A fractal structure of unclosed axionic walls, which is generated on the inflationary stage has been discussed in [20].

genetically related to the primary domain in which the phase originally exceeded  $\pi$ . It is evident that

$$N_j \approx \zeta^j; \quad M_j \approx M_0/e^{2j}. \quad (7)$$

Excluding  $j$  from these relationships, we obtain the desired black hole mass distribution in a cluster:

$$N_{cl}(M) \approx (M_0/M)^{\frac{1}{2} \ln \zeta}. \quad (8)$$

The total mass of the cluster can be expressed through the mass  $M_0$  of the largest initial black hole:

$$\begin{aligned} M_{tot} &= M_0 + \zeta M_1 + \zeta^2 M_2 + \dots = \\ &= M_0 + \zeta e^{-2} M_0 + (\zeta e^{-2})^2 M_0 + \dots = M_0 [1 - \zeta/e^2]^{-1}. \end{aligned} \quad (9)$$

As is seen, the total mass of the black hole cluster is only one and a half to two times greater than the largest initial black hole mass. The number of daughter black holes depends on the factors considered in the next section.

The inflationary mechanism described above leads to the occurrence of a fractal structure of the closed walls. After the end of inflation, as soon as the size of the horizon becomes larger than the characteristic size of closed walls, the walls begin to shrink. The energy of each wall, proportional to the area of their surface, concentrates in small spatial domains (in the following they are considered as point-like objects)[11, 21]. These high density clots of energy could serve in the following for star and/or galaxy formation (see for example [6] and references there). Hence, according to the given models, the distribution of stars and galaxies should have fractal properties as well. It is important to note that the total surface of the walls in definite volume is proportional to the total energy of an object, while the number of walls is equal to the number of dense clots.

Suppose, for a characteristic time  $1/H$ , that several closed walls appear in a causally connected area of size  $R$ , and the phase is still at the maximum of the potential. Denote the number of walls by  $N$  and their average size by  $\xi R$ ,  $\xi > 1/e$  ( $\xi \neq 1/e$  because of a possible merging of causally disconnected subdomains with one common wall). In each of these subdomains,  $N$  new, smaller closed walls of size  $\xi^2 R$  arise during the next time step. Denote by  $a$  the minimal size of such a wall that we are able to distinguish. This means that we may terminate the process after the  $n$ -th step such that  $a \equiv \xi^n R$ . The total area of the closed walls in the initial volume is the sum of the areas with closed walls of size greater than  $a$ . This simple summation leads to the following result:

$$S \approx R^2 q (q^n - 1)/(q - 1), \quad q \equiv \xi^2 N. \quad (10)$$

This expression can be written in the form

$$S \approx (R/a)^D, \quad (11)$$

where  $D$  is the fractal dimension. Equating these two expressions, one obtains

$$D = 2 + \frac{\ln \left( q^{\frac{\ln(a/R)}{\ln \xi} - 1} \right)}{\ln(R/a)}. \quad (12)$$

This quantity is constant only when the ratio  $R/a$  is large; it is different for  $q < 1$  and  $q > 1$ . It can be easily verified that  $D \rightarrow 2$  for  $q < 1$ , while for  $q > 1$ ,  $D \rightarrow 2 + 3 \ln(q)/\ln(4N)$ . To get an estimate, suppose that the number of closed domains is  $N \approx 4$ , and  $\xi \approx 1/e$ . The value of the parameter  $q$  can be easily calculated,  $q \approx 0.5$ . Hence, the fractal dimension of the system of closed walls  $D \approx 2$ .

So, if quantum fluctuations lead to the formation of spatial areas, with the phase taking a value near a potential maximum, its further evolution results in a system of enclosing walls. The characteristic size of the next generations of walls differs from the previous one by a factor of approximately  $e$ . The fractal dimension of such a system is  $D \approx 2$ .

According to this scenario, it is interesting to find the number of walls inside a sphere of radius  $R$ , which is given by

$$N_{tot} = \sum_{i=1}^n N^i = N \frac{N^n - 1}{N - 1} \approx \frac{N^{n+1}}{N - 1}. \quad (13)$$

By analogy with the previous calculations and using Eq. (13), one obtains the distribution of point-like dense objects with fractal dimension  $D' \approx \ln N / \ln(1/\xi)$ . For the realistic values  $N \approx 4$  and  $\xi \approx 1/e$ , we find  $D' \approx 1.4$ , which differs somewhat from the value  $D \approx 2$  previously obtained. This is not surprising since in the first case we measure the area of wall surfaces within a certain volume, while in the second case we measure the number of walls.

Let us compare our calculations with observational data of spatial distribution of galaxies and of stars in those galaxies. Recent data indicate that the distribution of stars and galaxies indeed carries a fractal character. So the number of galaxies inside a sphere of radius  $R$  is  $N(R) \sim (R)^{2.2 \pm 0.2}$  up to a sizes of 200 Mpc [22].

The distribution of stars inside galaxies also carries a fractal character. In Ref.[23] this fractal dimension was determined by averaging observational data from ten galaxies; it was found to be equal to  $D \sim 2.3$ .

Evidently, the observable fractal dimension  $D$  in distributions of stars and galaxies is in agreement with predictions of our model. Of course, other mechanisms, at a later stage, may contribute to the distribution and change the fractal dimension somewhat, but the scenario of PBHs formation, discussed here, could give a primordial reason of fractality in the galaxy and star distribution.

The mechanism of fractal structure production discussed in this paper is not unique. Another example is based on hybrid inflation, one of the most promising models of inflation [24, 25, 26]. In the standard version of hybrid inflation the potential contains two fields

$$V = V_0 + \frac{1}{2} m_\varphi^2 \varphi^2 + \frac{1}{2} \lambda_1 \varphi^2 \psi^2 - \frac{1}{2} m_\psi^2 \psi^2 + \frac{1}{2} \lambda_2 \psi^4. \quad (14)$$

During inflation, the field  $\varphi$  rolls down along a valley  $\psi = 0$ . In the meantime field fluctuations around the critical line  $\psi = 0$  lead to the formation of a fractal structure of domains. This critical line plays the same role as the critical point  $\pi$  in the previous discussion. Just after passing the critical point  $\varphi = m_\psi^2 / \lambda_1$ , the state  $\psi = 0$  becomes

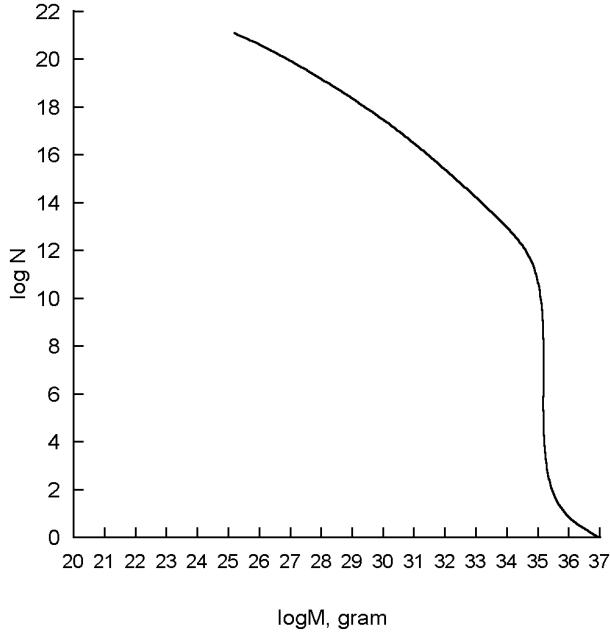


Figure 1: *The numerically simulated distribution of PBHs, where  $f = 1.77H$  and  $\Lambda = 5\text{ GeV}$ . It is supposed that the Universe underwent 60 e-folds of inflationary expansion with the Hubble constant  $H = 10^{13}\text{ GeV}$ .*

unstable and field  $\psi$  moves (on average) to one of the new stable minima. These minima are separated by a potential maximum and we again inevitably come to the fractal structure of domain walls.

## 4 DISCUSSION

In the preceding sections, we considered only the principal possibility of the formation of domain walls connecting adjacent vacuum states. We have used the formulas derived above to estimate the efficiency of the proposed mechanism of the black hole cluster formation. The numerical calculations [21] were performed for the following values of the parameters (which are consistent with the observed anisotropy in the cosmic microwave radiation): the Hubble constant at the end of inflation,  $H = 10^{13}\text{ GeV}$ ; Lagrangian parameters,  $f = 1.77H$  and  $\Lambda = 5\text{ GeV}$ . The initial phase, at which the visible part of the Universe is formed between the time  $t_U \approx 60H^{-1}$  to the end of inflation, controls the number of domains and, accordingly, the number of closed walls formed in the post-inflation stage. This random value, not related to the Lagrangian parameters, must be selected, taking into account the numerous restrictions on the abundance of PBHs in the Universe (see for example [6] and

references there). We will use the numerical value  $\theta_U = 0.05\pi$ , which ensures a sufficiently large number of massive black holes, while the presence of numerous smaller ones does not contradict experimental restrictions. As is seen in Fig.1, the PBH masses fall within the range from  $10^{25}$  to  $10^{35}$  g. The initial phase  $\theta_U$  was selected so as to provide for the number of massive PBHs (with mass  $\sim 10^{35}$  g) to be equal to the number of galaxies in the visible part of the Universe. The total mass of black holes is supposed to be  $\sim 1\%$  of the contemporary baryonic contribution.

The results of these calculations are sensitive to changes in the parameter  $\Lambda$  and the initial phase  $\theta_U$ . As the  $\Lambda$  value decreases to  $\approx 1$  GeV, still greater PBHs appear with masses of up to  $\sim 10^{40}$  g. A change in the initial phase leads to sharp variations in the total number of black holes. As was shown above, each domain generates a family of subdomains in the close vicinity. The total mass of such a cluster is only 1.5–2 times that of the largest initial black hole in this space region. Thus, our calculations confirm the possibility of formation of clusters of massive PBHs ( $\sim 100M_\odot$  and above) in the earliest stages of the evolution of the Universe at a temperature of  $\sim 1 - 10$  GeV. These clusters represent stable energy density fluctuations around which increased baryonic (and cold dark matter) density may concentrate in the subsequent stages, followed by the evolution into galaxies.

It should be noted that additional energy density is supplied by closed walls of small sizes. Indeed, because the smallness of their gravitational radius, they do not collapse into BHs. After several oscillations such walls disappear, leaving coherent fluctuations of the PNG field. These fluctuations contribute to a local energy density excess, thus facilitating the formation of galaxies.

## 5 CONCLUSIONS

This paper proposes a new mechanism for the formation of protogalaxies, which is based on the cosmological inferences of the elementary particle models predicting non-equilibrium second order phase transition [11] in the inflation stage period and the formation of a domain wall upon the end of inflation. The presence of closed domain walls of a size markedly exceeding the cosmological horizon in their period of formation leads to the collapse of the wall in the post-inflation epoch (when the wall size becomes comparable with the cosmological horizon); this results of a formation of massive black hole clusters that can serve as nuclei for the future galaxies. The mass spectrum of PBHs do not contradict the available restrictions. The number of black holes with  $M \sim 100M_\odot$  and above is comparable with the number of galaxies in the visible Universe. Processes of deceleration of the wall motion, which have been considered in [21], may affect only the dynamics of collapse of supermassive walls, which are beyond of the scope of this paper.

A development of the proposed approach gives ground for a principally new scenario of the galaxy formation in the model of the hot Universe. Traditionally, the hot Universe model assumes a homogeneous distribution of matter on all scales, whereas the appearance of observed inhomogeneities is related to the growth of small initial density perturbations.

However, the analysis of the cosmological consequences of the particle theory indicates the possible existence of strongly inhomogeneous primordial structures in the distribution of both the dark matter and baryons. These primordial structures represent a new factor in galaxy formation theory. Topological defects such as the cosmological walls and filaments, primordial black holes, archioles in the models of axionic CDM [7], and essentially inhomogeneous baryosynthesis (leading to the formation of antimatter domains in the baryon-asymmetric Universe) [27] offer by no means a complete list of possible primary inhomogeneities inferred from the existing elementary particle models.

The proposed approach discloses a number of interesting aspects in this direction. Indeed, our model offers a possibility of quantitative analysis of correlations in the formation of massive PBHs and the primary inhomogeneity of dark matter and baryons. Originally inherent in this mechanism is the inhomogeneous phase distribution, which eventually acquires (much as what takes place in the invisible axion cosmology) a dynamical sense of the initial amplitude of the coherent oscillations of a scalar field. Irrespective of the efficiency of dissipation of the energy of these oscillations, the regions of closed wall formation must be correlated with the regions of maximum energy density of the latent mass. If these oscillations are not decaying, their energy density may provide for the contemporary CDM density. Inhomogeneity in the initial amplitude of these oscillations would then imply the inhomogeneity in the initial energy density and, hence, the regions of black hole formation would become the regions of increased dark matter density.

A qualitatively similar effect (albeit not as pronounced) takes place in the dissipation of coherent oscillations at the expense of particle production. An increase in the oscillation energy density transforms into a local increase in the density of latent mass particles produced in this region.

The development of the proposed approach may thus lead to a number of interesting scenarios of the initial stages in the formation of protogalaxies, depending on the selection of particular elementary particle models and their parameters. This study presents the first step in this direction.

## 6 ACKNOWLEDGMENTS

The authors are grateful to E.D. Zhizhin and A.A. Starobinsky for their interest in this study. The work of M.Yu.Kh. and S.G.R. was partly performed within the framework of the "Cosmoparticle Physics" Project of the State Scientific - Technological Program "Astronomy. Fundamental Space Research", and it was supported by the Cosmion-ETHZ, Epcos-AMS international cooperations and Scientific School Support Grant no. 00-15-96699. One of us (M.Yu.Kh.) expresses his gratitude to IHES and ICTP for hospitality, while finishing the work on this paper. We are also grateful to J. Ellis for useful comments.

## References

- [1] B.Ya. Zel'dovich and M.Yu. Khlopov, Phys. Lett. **B79**, 1134 (1978).
- [2] A. Guth, Phys. Rev. **D23**, 347 (1981).
- [3] Ya.B. Zel'dovich, I.Y. Kobzarev and L.B. Okun, Sov. Phys. JETP **40**, 1 (1975).
- [4] T.D. Lee, Phys. Rev. **D8**, 1226 (1973).
- [5] Ya.B. Zel'dovich, MNRAS **192**, 663 (1980); A. Vilenkin, Phys. Rev. Lett. **46**, 1169 (1981).
- [6] M.Yu. Khlopov, *Cosmoparticle Physics* (World Scientific, Singapore, 1999).
- [7] M.Yu. Khlopov and A.S. Sakharov, Phys. Atom. Nucl. **57**, 485 (1994); M.Yu. Khlopov, A.S. Sakharov and D.D. Sokoloff, ibid. **59**, 1005 (1996); Nucl. Phys. Proc. Suppl. **72**, 105 (1999).
- [8] D.E. Rosenberg and J.R. Rutgers, astro-ph/0012023 (2000).
- [9] S. Veilleux, astro-ph/001212 (2000).
- [10] M. Stiavelli, astro-ph/9801021 (1998).
- [11] S.G. Rubin, M.Yu. Khlopov and A.S. Sakharov, Gravitation & Cosmology, Supplement **6**, 51 (2000).
- [12] F.C. Adams et al., Phys. Rev. **D47**, 426 (1993).
- [13] A. Starobinsky, JETP Lett. **30**, 682 (1979); Phys. Lett. **91B**, 99 (1980).
- [14] S.G. Rubin and A.S. Sakharov, in progress
- [15] A. Vilenkin and E.P.S. Shellard, *Cosmic Strings and other Topological Defects* (Cambridge University Press, Cambridge, 1994).
- [16] P. Sikivie, Phys. Rev. Lett. **48**, 1156 (1982).
- [17] J.E. Kim, Phys. Rep. **150**, 1 (1987).
- [18] V.A. Berezin, V.A. Kuzmin and I.I. Tkachev, Phys. Lett. **120B**, 91 (1983).
- [19] J. Ipser and P. Sikivie, Phys. Rev. **D30**, 712 (1984).
- [20] A. Linde, D. Linde and A. Mezlumian, Phys. Rev. **D49**, 1783 (1994).
- [21] S.G. Rubin, A.S. Sakharov and M.Yu. Khlopov, JETP **92**, 921 (2001) [hep-ph/0106187].

- [22] S. Labini, M. Montouri, and L. Pietronero, Phys. Rep. **293**, 61 (1998).
- [23] B.G. Elmegreen and D.M. Elmegreen, astro-ph/0012184 (2000).
- [24] A. D. Linde, Phys. Lett. **259B**, 38 (1991).
- [25] G. Dvali, Q. Shafi and R. Schaefer, Phys. Rev. Lett. **73**, 1886 (1994).
- [26] D.H. Luth, hep-ph/990471 (1999).
- [27] M.Yu. Khlopov, S.G. Rubin and A.S. Sakharov, Phys. Rev. **D62**, 083505 (2000).